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Engineering Reliability Analysis for Prioritizing Investment Decisions

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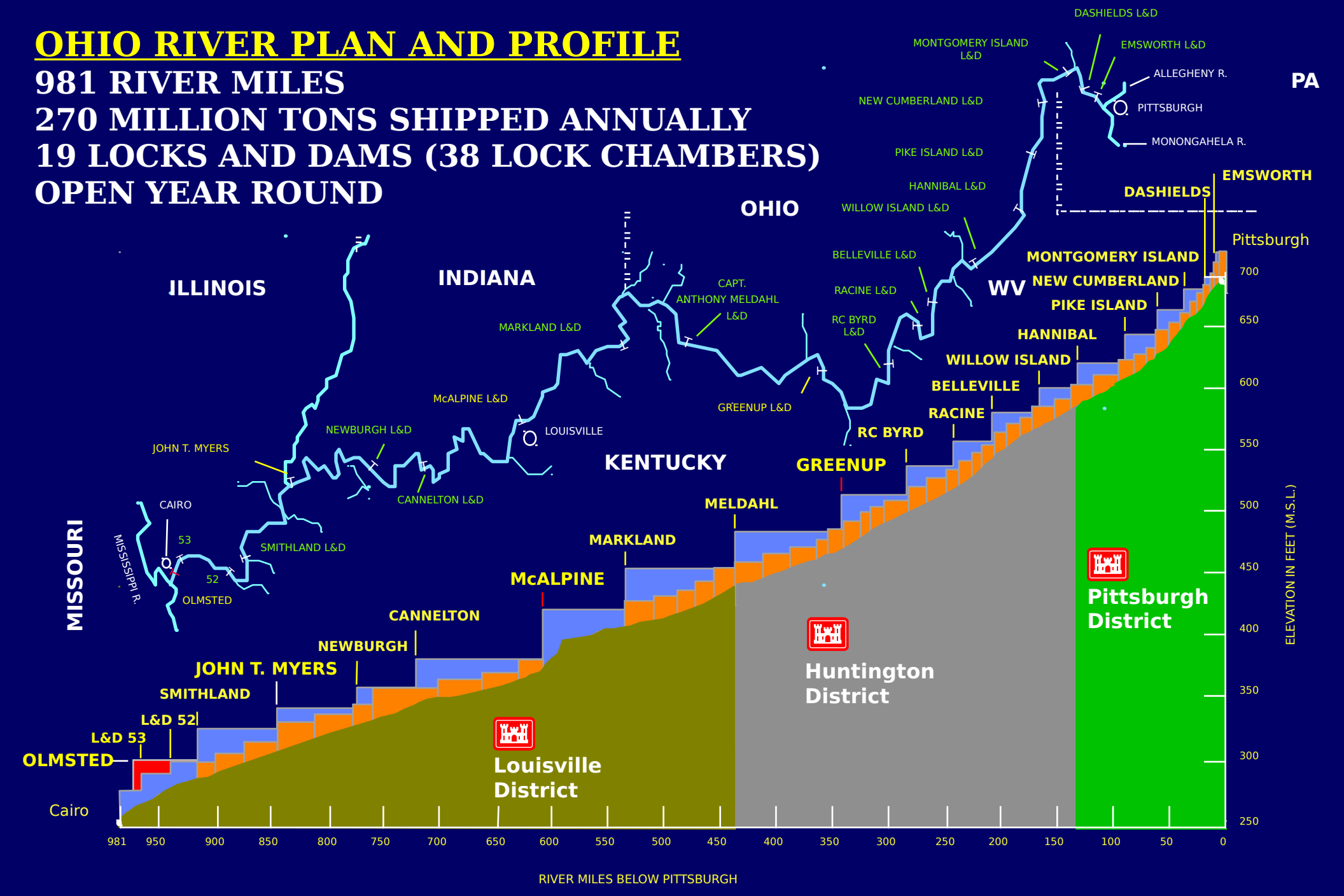
Outline of Presentation

- Existing System of Ohio River Locks and Dams
- Ohio River Mainstem Systems Study
  - *Engineering Reliability Features*
  - *Integration with Economics*
- Ohio River Navigation Investment Model
  - *Capabilities and Uses*
- Future and On-Going Studies
  - *Great Lakes/St. Lawrence Seaway & Panama Canal*

OHIO RIVER PLAN AND PROFILE

981 RIVER MILES
270 MILLION TONS SHIPPED ANNUALLY
19 LOCKS AND DAMS (38 LOCK CHAMBERS)
OPEN YEAR ROUND



Markland Locks and Dam (Typical Configuration)

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Ohio River Project Details

Project	District	Year Built	Annual Tonnage	Annual Recreational Vessels	Annual Number Tows
Emsworth	LRP	1921	23,000,000	5,300	4,000
N.Cumberland	LRP	1959	37,000,000	4,600	1,800
Hannibal	LRP	1972	46,000,000	4,300	900
Willow Island	LRH	1972	44,000,000	3,800	1,600
RC Byrd	LRH	1993	59,000,000	5,400	700
Greenup	LRH	1959	70,000,000	6,400	700
Markland	LRL	1959	55,000,000	5,200	4,100
John T. Myers	LRL	1975	72,000,000	6,600	2,500
Olmsted*	LRL	2014	94,000,000	9,900	1,700

(* Current Level)

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Ohio River Mainstem Systems Study

Assessing the Condition of All Project Features

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Engineering Reliability Analysis

What is it? Why is it used? What is the Justification for its Use?

- Required by USACE Guidance for Specific Types of Investments
  - Major Rehabilitation Projects (Markland, Emsworth, J.T. Myers)
  - New Project Authorization Based Upon Deteriorated Condition of Existing Project (Chickamauga)
  - Systems Studies Recommendations (ORMSS and GLSLS)
- Recognizes and Captures Uncertainty in Engineering and Economic Analyses
  - Engineering Uncertainties – Loads, Material Properties, Corrosion, Fatigue
  - Economic Uncertainties – Traffic Forecasts, Rate Savings
- Shows Economic Justification and Risks Associated with Multiple Future Investment Alternatives
  - Fix-as-Fails Maintenance, Advance Maintenance, Major Rehab
- Allows an Unbiased Method to Rank Projects Based Upon Risks and Economic Merit

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Ohio River Mainstem Systems Study

Forecasting the Future

- Traffic Forecasts
- Lock Capacity
- Lock Reliability
  - Structural condition of lock and dam components
  - Cost of repairing lock components compared to replacing components ahead of failure
  - Operational effect of lock repairs (do they cause significant impacts to navigation, pool levels, and/or other impacts)

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Ohio River Mainstem Systems Study

Introduction to Systematic Evaluation

- Investment Plan for Ohio River Navigation System for 2005 - 2065
- Multi-Project, Multi-District, Multi-Discipline
  - Pittsburgh, Huntington, and Louisville Districts
  - Engineering, Economics, Plan Formulation, and Environmental
- Prioritization Among Maintenance, Rehabs, New Construction for All 19 Projects
  - Projects ages vary from 80+ years to under construction
  - Traffic levels and lock chamber dimensions vary
- Reliability Had Significant Impact on Economic Analysis and was used to Time Improvements

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ORMSS
Engineering Reliability Integration

- Aging System of Locks and Dams
  - Most projects approaching original design life of 50 years
  - Most projects will be near 100 years old by end of study
- Older, Deteriorated Projects Need Condition Upgrades
- High Traffic Projects Need Capacity Enhancements
- Reliability Used to Justify and Time Project Upgrades
- Most Critical System Components Analyzed
  - Excessive repair cost and/or excessive down time
- Bottom Line – Where is Best Place to Put Limited Funds???

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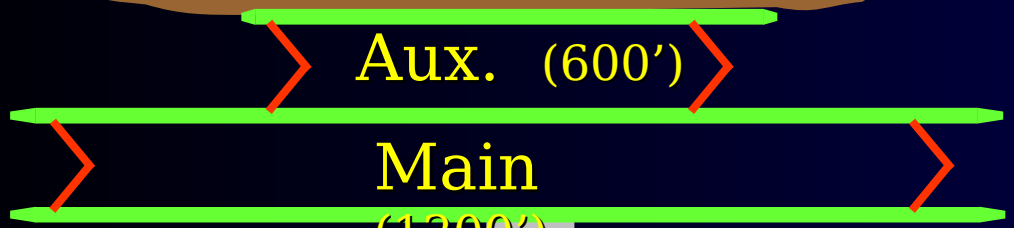
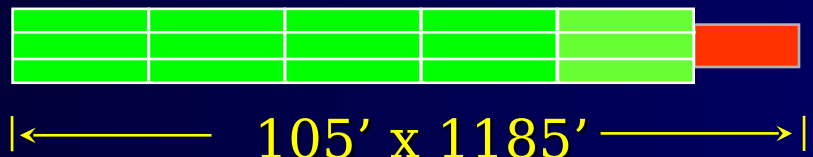
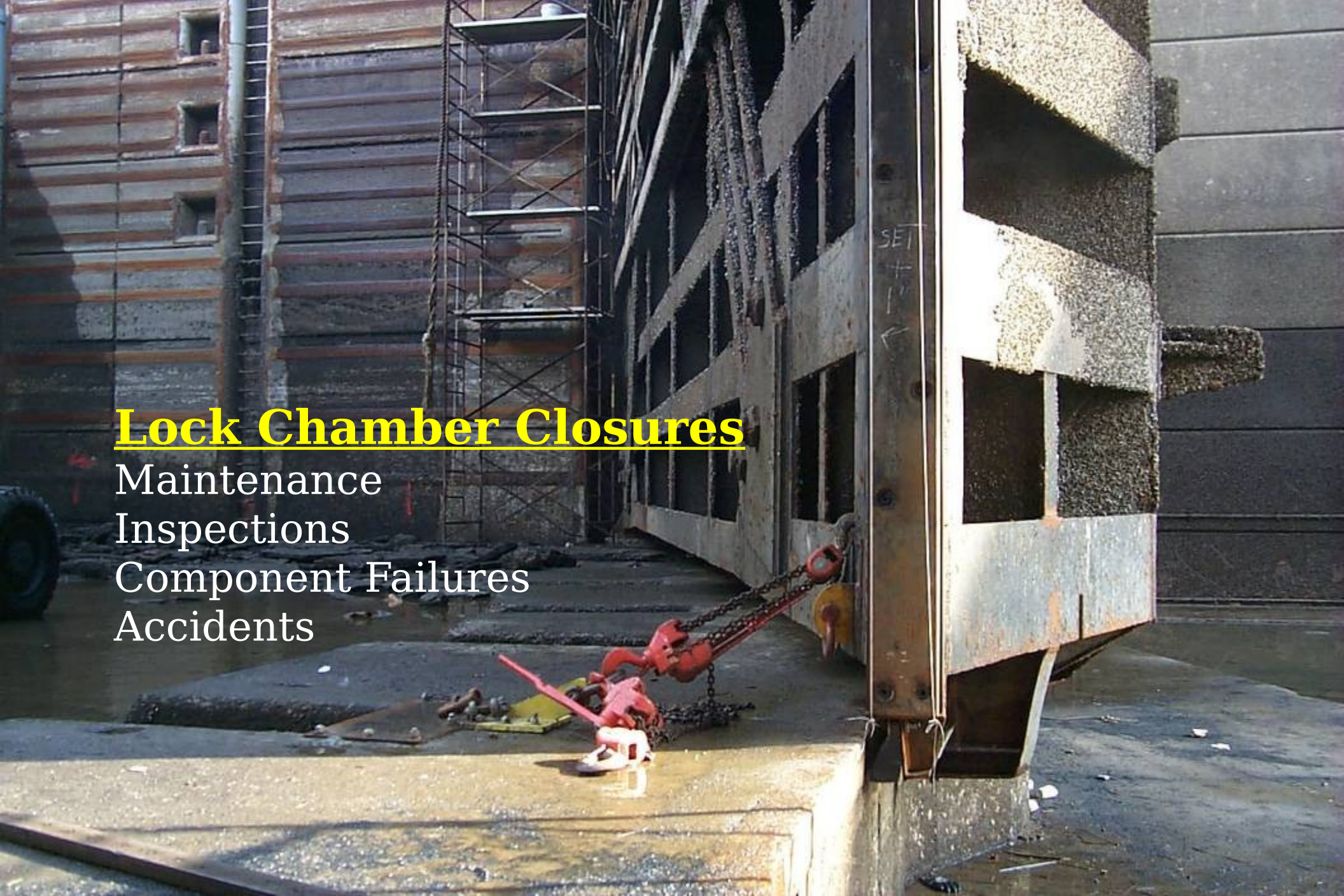
Typical Ohio River Main & Auxiliary Locks





Typical 15 Barge Tow

Dam



Lock Chamber Closures

Maintenance
Inspections
Component Failures
Accidents

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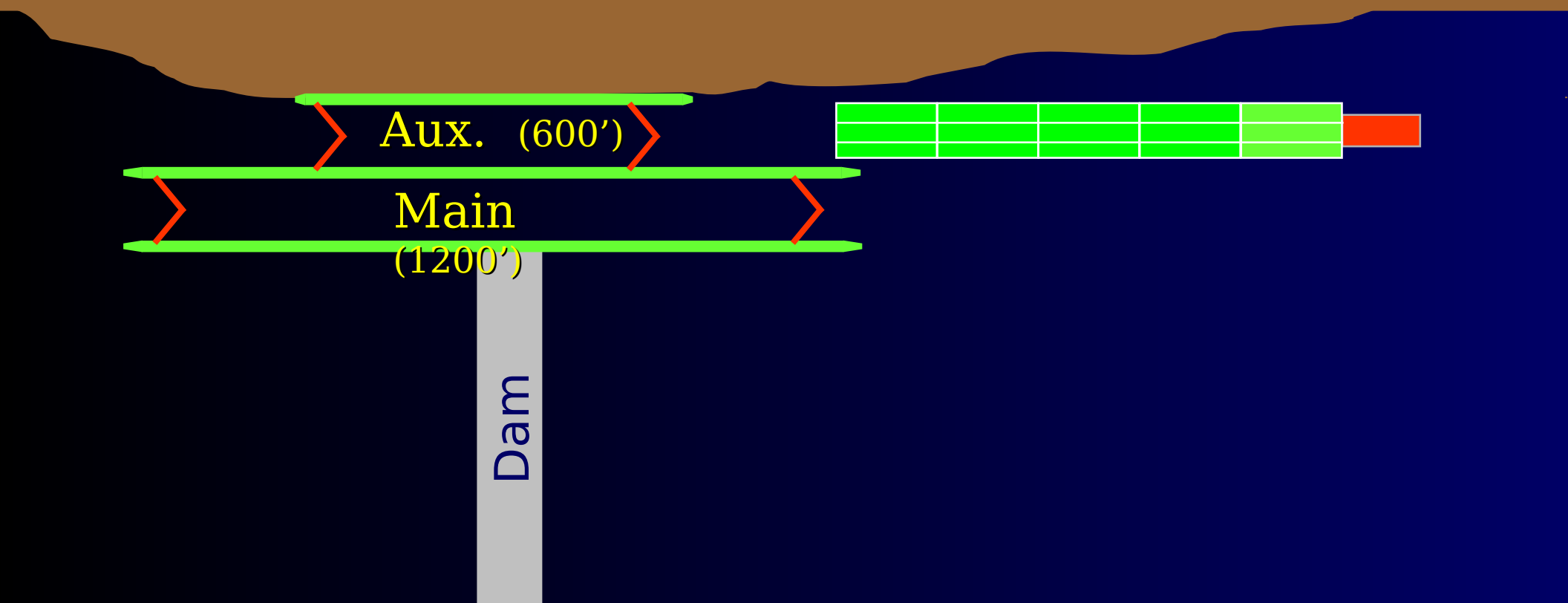
Typical Ohio River Use of Auxiliary Locks



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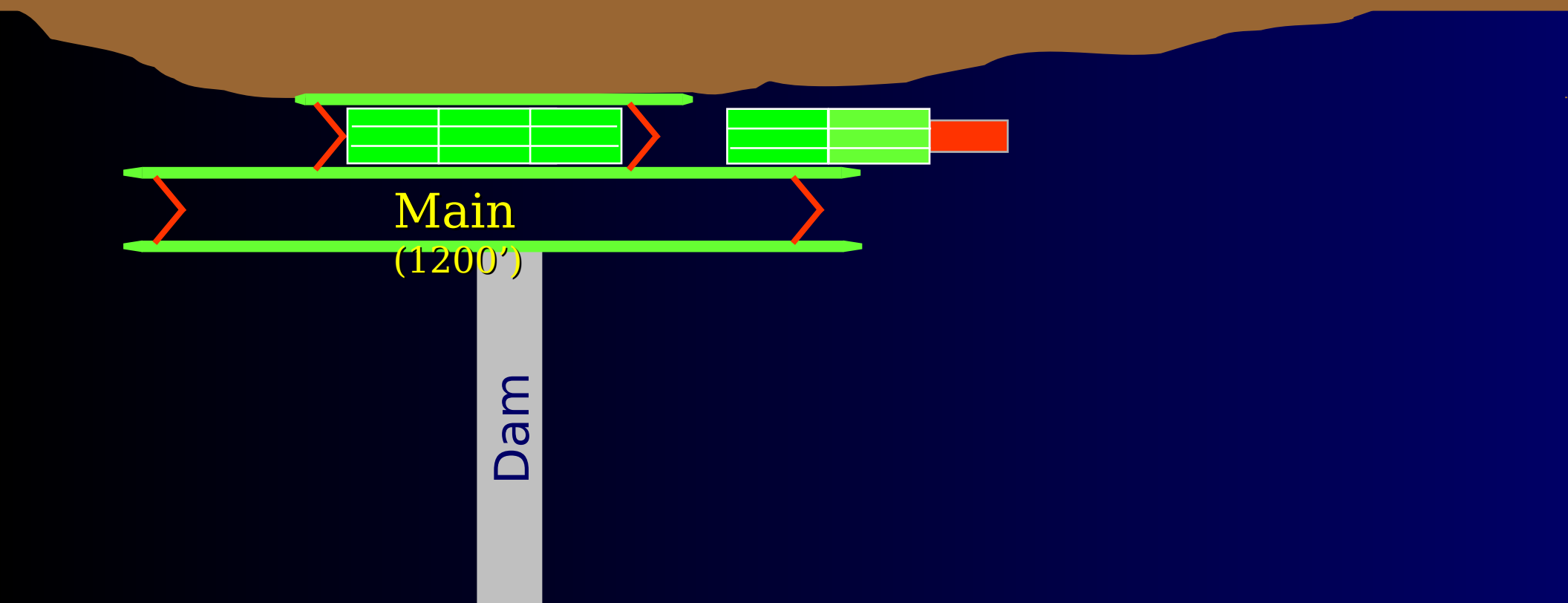
Typical Ohio River
Use of Auxiliary Locks



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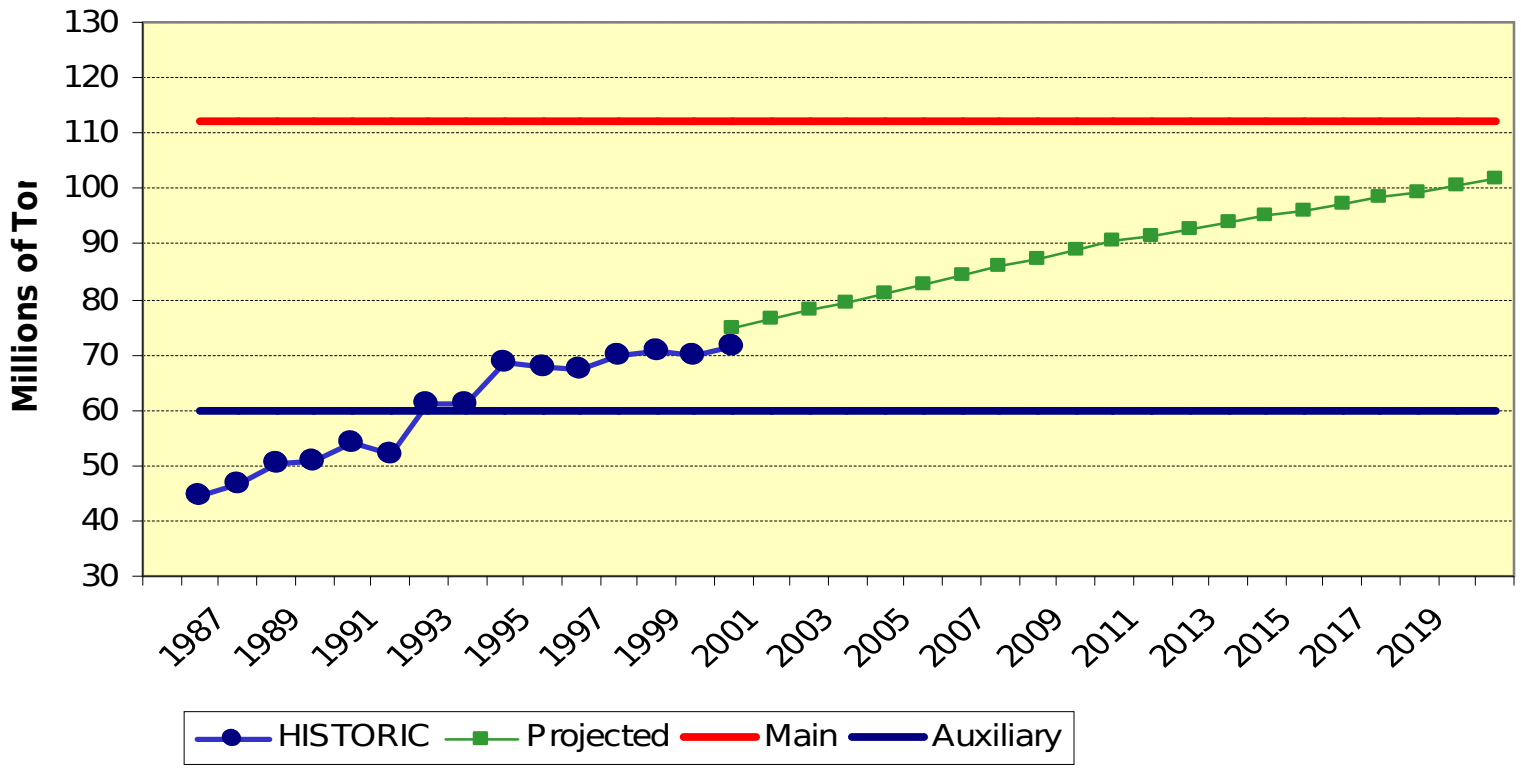
Assessment of Needs

Capacity & Traffic



McAlpine 1999 Main Chamber Dewatering

Tows Waiting to Lock Through
Short, Inefficient Auxiliary Chamber

Upper Ohio River Delays During Main Chamber Dewatering

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Economic Impacts of Main Closures

Examples of Recent Ohio River Closures

Event	Duration	Delay Cost	Repair Cost	Total Cost	Peak Delay
Aug. 2003	15 days	$1,200,000	$800,000	$2,000,000	33 hours
Sept. 1999	15 days	$3,100,000	$800,000	$3,900,000	86 hours (3 ½ days)
July/August 1997	36 days	$12,900,000	$2,600,000	$15,500,000	144 hours (6 days)

August 2003 closure of Markland 1200’ chamber for inspection & repairs
September 1999 closure of McAlpine 1200’ chamber for miter gate repairs
July/August 1997 closure of McAlpine 1200’ chamber for major maintenanc

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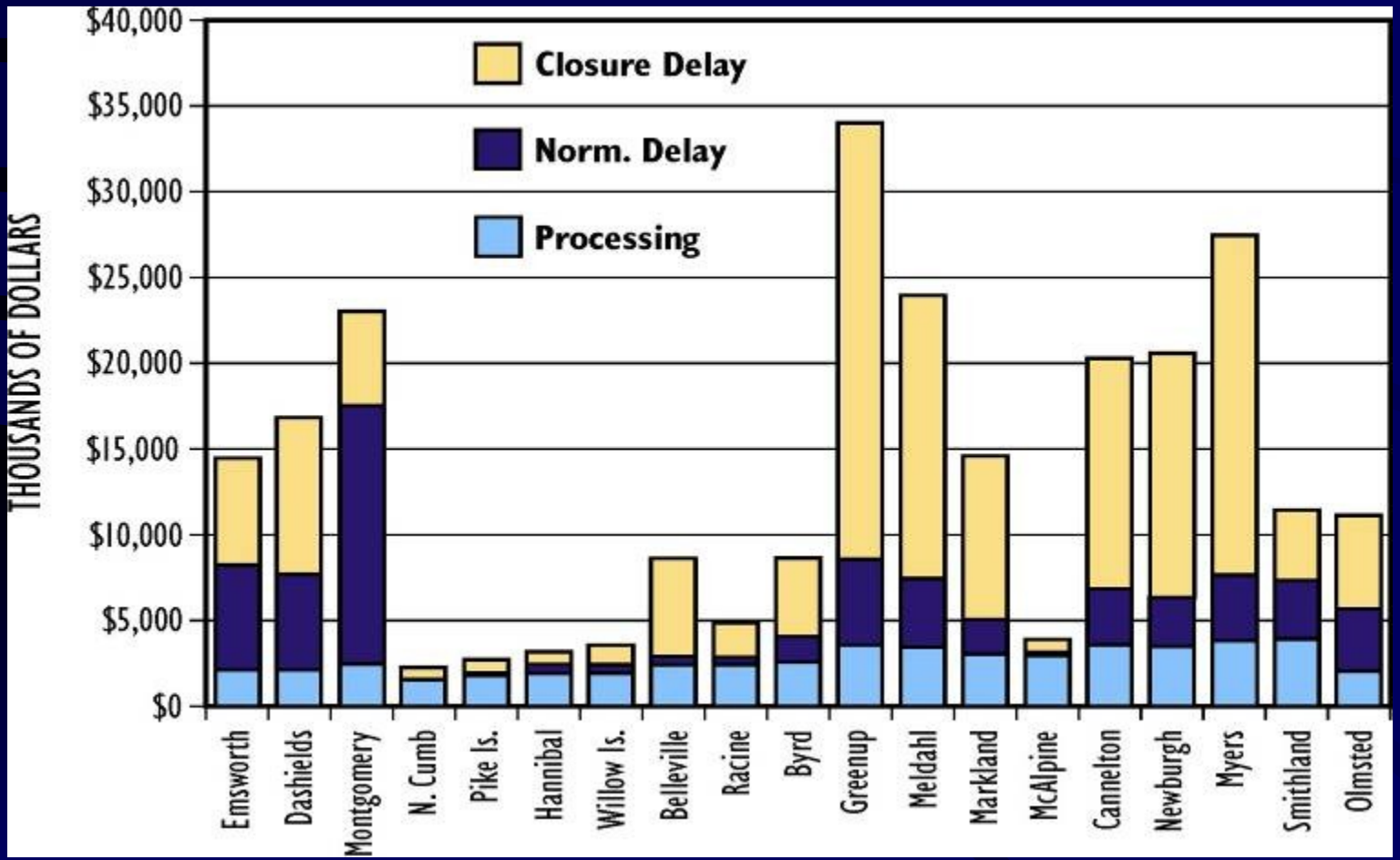
ORMSS Economic Impact

Average Annual Transit Costs by Category

FUTURE CONDITION W/O LARGE-SCALE IMPROVEMENTS



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ORMSS Reliability Integration

Selection of Critical Components

- Two Phase Screening Process Used to Select Components
  - Site Inspections, Interviews, Review of Plans Led to Global List of 170 Components
  - Phase 1 Screening Eliminated Components of Low Consequence (60 Survived)
  - Phase 2 Screening Used a Numerical Rating System (15 Survived)
- 15 Components Required Reliability Modeling
  - Non-Time Dependent Components
  - Time Dependent Components

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ORMSS Reliability Integration

Types of Components

- **Non-Time Dependent Components**
  - Typically Gravity Structures That Do Not Change With Time
  - Analyzed for Multiple Failure Modes
  - Multiple Load Cases
  - Reliability Model Produces PUP's That Remain Constant

- **Time Dependent Components**
  - Structures That Degrade Over Time
  - Example - Steel Structures Subject to Corrosion and Fatigue
  - Reliability Model Produces Hazard Functions

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Non-Time Dependent Components

STABILITY ANALYSIS OF UNANCHORED GRAVITY STRUCTURES

- Land, River, Middle Wall Monoliths
- Guide and Guard Wall Monoliths
- Miter Gate Monoliths
- Miter Gate Sills

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Non-Time Dependent Components

LOAD CASES

Normal Operating
Maintenance Dewatering

LIMIT STATES

Sliding at the Base
Deep-Seated Sliding
Overturning
Bearing Capacity

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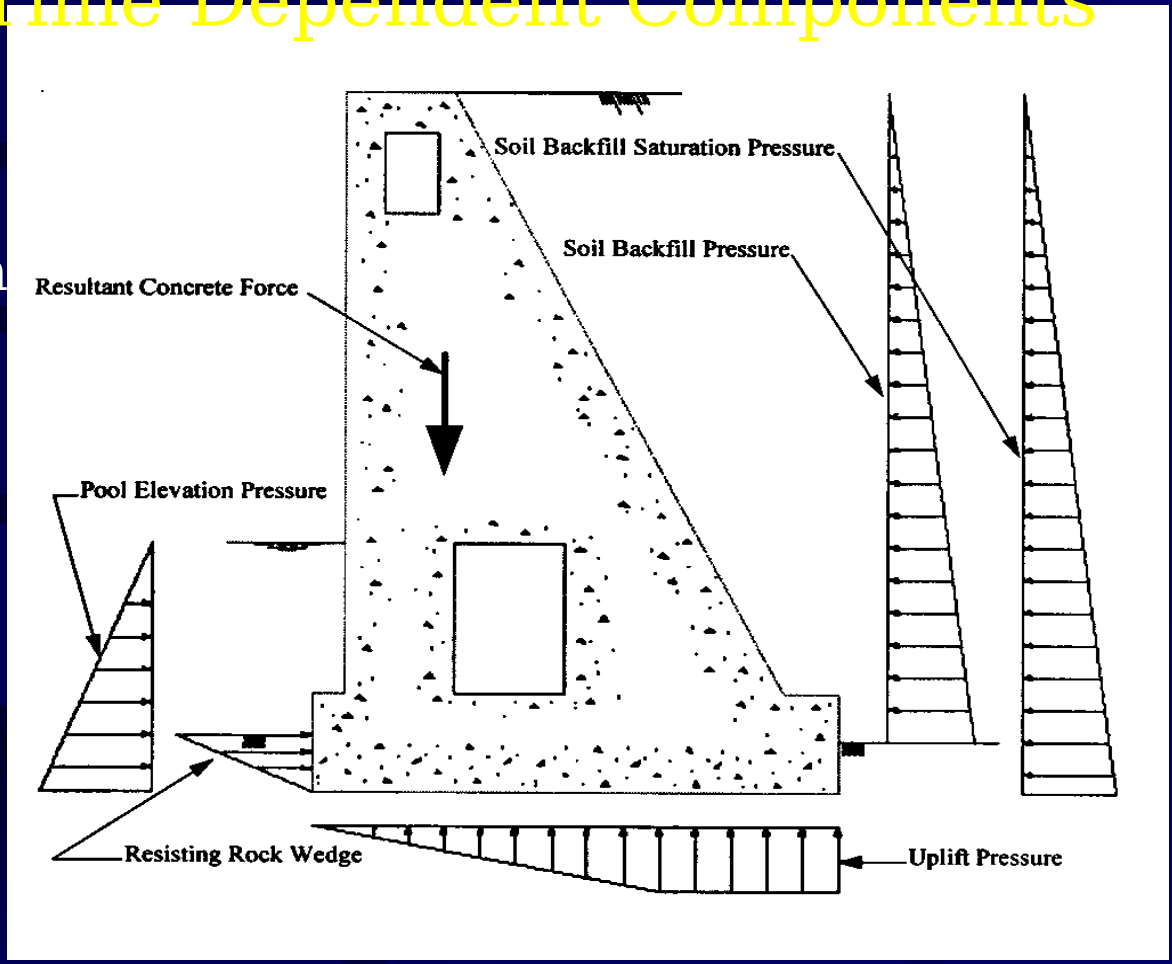
Non-Time Dependent Components

Random Variables

- Lower Pool Elevation
- Soil Unit Weights and Strength
- Soil Backfill Saturation Level
- Rock Strengths
- Barge Impact Force
- Hawser Force

Constants in Analysis

- Upper Pool Elevation
- Concrete Unit Weight
- Water Unit Weight



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ORMSS Reliability Integration

Non-Time Dependent Model Details

- **10,000 Iterations for Normal Load Case**
  - Monte Carlo Simulation of Random Variables Used
  - @Risk™ Software Used for Simulation
  - Spread Sheets Used for Computations
  - Analysis Produces Single PUP for Normal Load Case
- **10,000 Iterations for Maintenance Case**
  - Lock Chamber Dewatered Every 5 Years On Average
  - Typically Represents Worst Load Case for Lock Wall Stability
  - Analysis Produces Single PUP for Maintenance Load Case
- **Event Tree Formatted for Both Load Cases**

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ORMSS Reliability Integration

Time Dependent Components

STRUCTURAL MODELS

HF Miter Gates
VF Miter Gates
Anchored Monoliths
Anchored Sills
HF Culvert Valves
VF Culvert Valves

MECHANICAL/ELECTRICAL

MG Machinery
CV Machinery
Lock Hydraulic
Lock Electrical

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ORMSS Reliability Integration

Establish the Current Condition of Structure

CULVERT VALVE FAILURES

MITER GATE FAILURES

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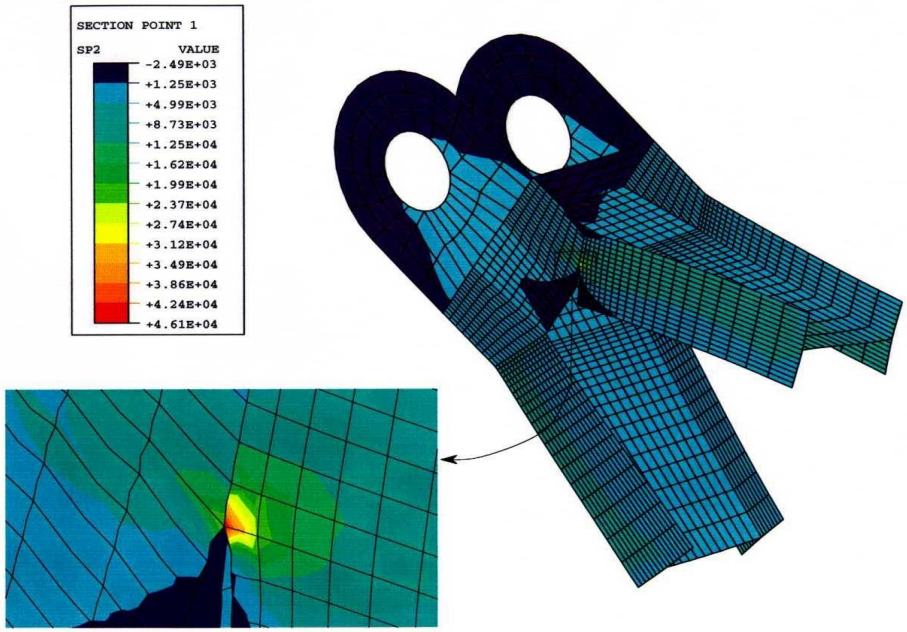
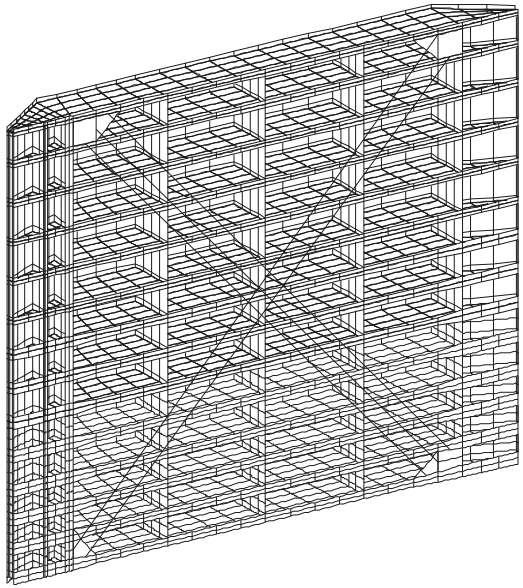
Advanced Modeling for Realistic Failure Modes

LOCAL F.E. MODELING

- Establishes Residual Stress Distribution
- Crack Initiation and Propagation
- Benchmark with Field Cracking/Measurements





GLOBAL F.E. MODELING

- Load Distribution on Global Structure
- Stress Distribution for Varying Ops
- Determination of Areas of High Stress

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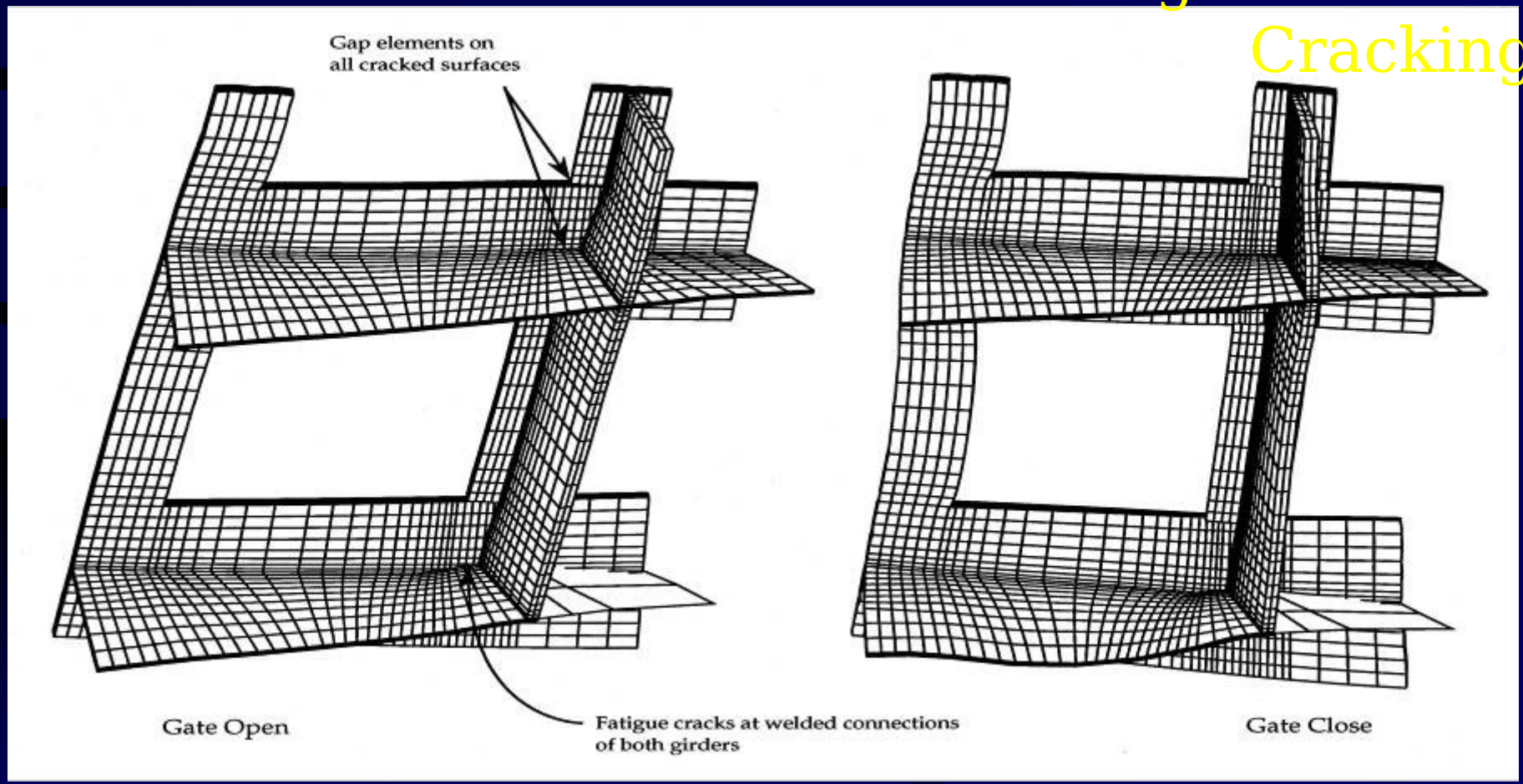
Modeling for Field Limit States

Failure Due to Fatigue-Related Cracking



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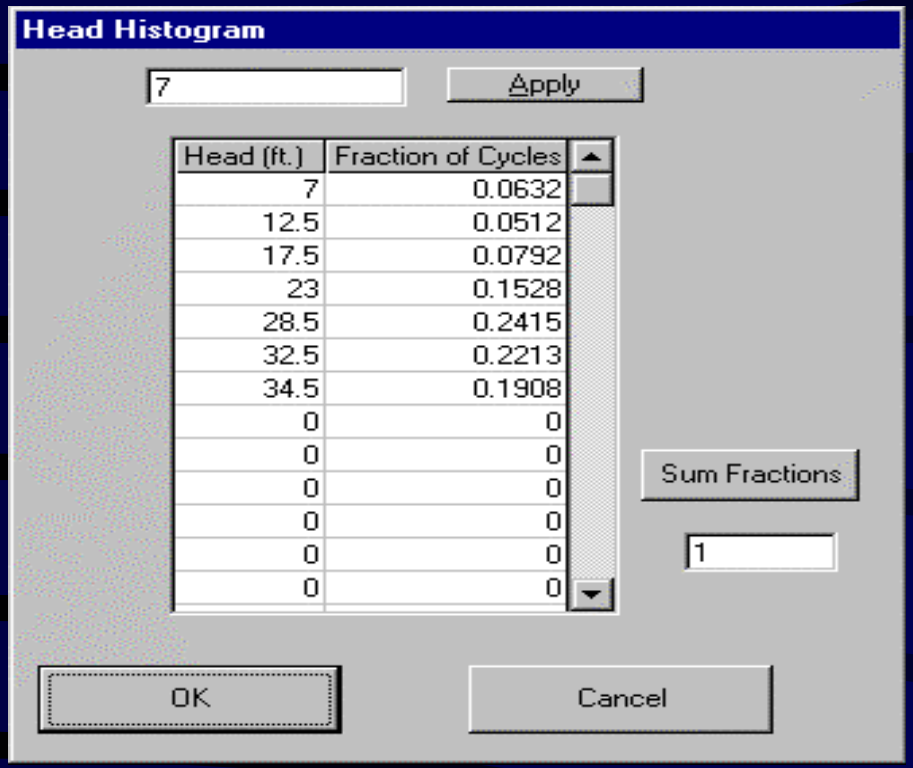
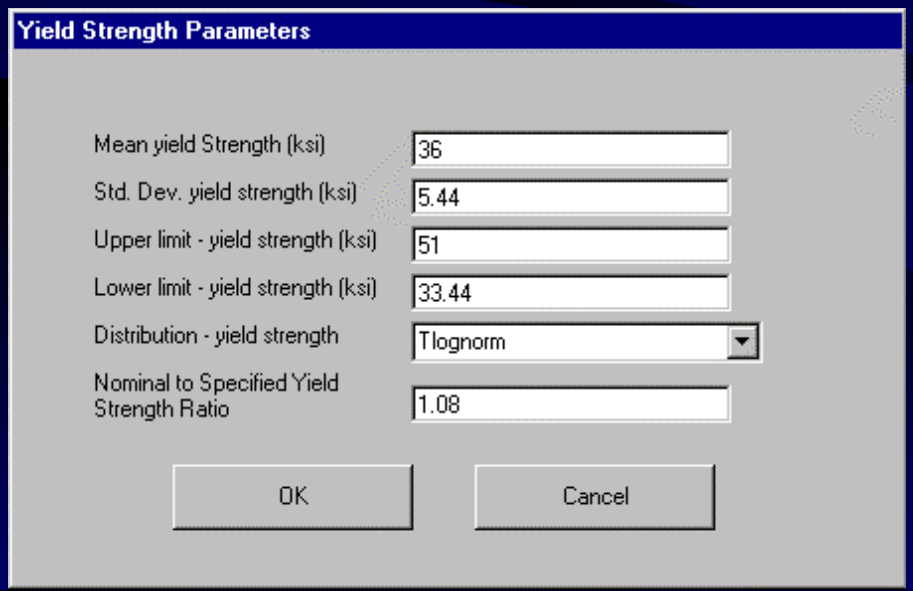
Time Dependent Reliability Modeling

Summary of Model Features

- Miter Gate and Culvert Valve Reliability
  - F.E. Modeling Used as Basis for Reliability Model Input
  - Calibration and Limit State Developed Using F.E. Modeling
  - Custom Coded Reliability Model Developed in Visual Basic
  - Monte Carlo Simulation (Speed Allowed 50,000 Iterations)

- Mechanical and Electrical Models Were Developed using Failure Rates from Established Publications Within MS Excel Spreadsheet




Yield Strength Parameters
Mean yield Strength (ksi) 36
Std. Dev. yield strength (ksi) 5.44
Upper limit - yield strength (ksi) 51
Lower limit - yield strength (ksi) 33.44
Distribution - yield strength Tlognorm
Nominal to Specified Yield Strength Ratio 1.08
OK
Cancel

Example HWELD Input Menus

- Miter Gate Properties
  - Girder Spacing, Length
  - Skin Plate Properties
- Girder/stiffener properties
  - Flange, Web Thickness
- Operating Cycles
  - Historic and Projected
- Yield Strength of Steel (Random)
- Corrosion Parameters (Random)
- Stress Concentration Factors (Random)
  - Determined from F.E. Modeling
- Pintle Wear / Misalignment Factor (Rand
  - Determined from F.E. Modeling
- Head Histogram (Acts Random)
  - Determined from LPMS Data
- Maintenance Strategy
  - Fix-As-Fails, Adv. Maintenance, etc.

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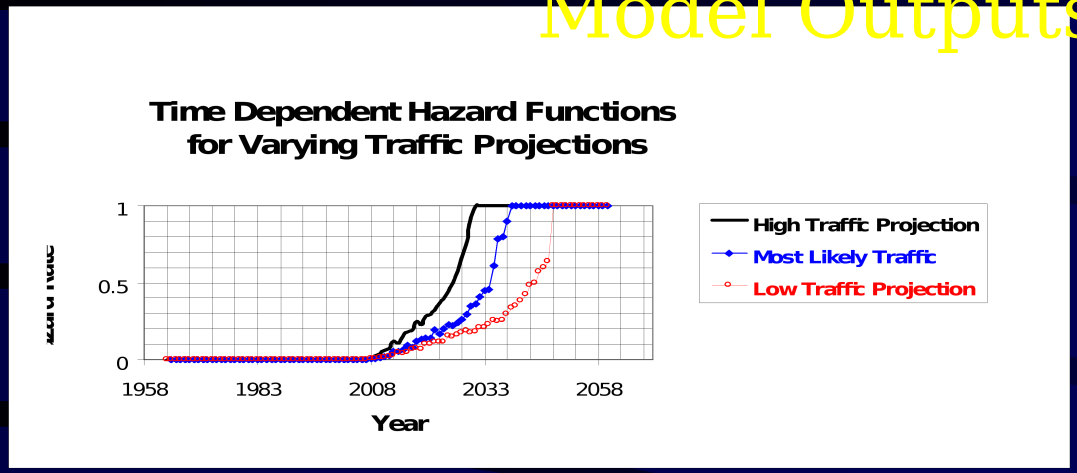
ORMSS Reliability Integration

Model Outputs and Integration with Economics



Time dependent probabilities of failure for various alternatives through study period

Component		Annual Hazard Rate	Level of Repair	Closure Time	Repair Cost	Effect on Overall Component Reliability
		Annual Reliability Value (1 - Annual Hazard Rate)				
Horizontally-framed Miter Gate			New Gate 5%	365 days in year 1 90 days in year 2	$13,150,000 $3,150,000	Assume R = 1.0 for All Future Years
		Annual Hazard Rate	Major Repair 35%	45 days in year 1 45 days in year 2	$1,575,000 $1,575,000	Move Back 5 Years
			Temporary Repair 60% Replace 1st Set of Gates Replace 2nd Set of Gates	45 days in year 1 45 days in year 2 30 days in year 3	$3,575,000 $3,575,000 $5,050,000	Assume R = 1.0 for All Future Years
SCHEDULED REPLACEMENT BEFORE FAILURE INFORMATION Year 1 -- 30 Days of Closure @ $5,050,00 Year 2 -- 30 Days of Closure @ $5,050,000 Future Reliability Will Equal 1.0 Throughout Remainder of Study Period						

Consequence event tree given the limit state is exceeded in the reliability analysis

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Optimized Timing of Component Replacement

- Economic Model (ORNIM)
  - C+ Model Written to Integrate Engineering & Economics
  - Uses Hazard Rates & Event Tree Information
  - Computes Average Annual Costs Associated with Failures
  - Accounts for Component Repair & Navigation Delay Costs
- Different Alternates Tested Consistent with Formulation
  - Fix-As-Fails Baseline Condition
  - Other Maintenance Scenarios (Advance Maintenance)
  - Scheduled Rehabilitations or New Projects

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Example of Reliability-Based Economic Evaluation

MAIN CHAMBER GATE RESULTS FOR OHIO RIVER LOCK

Scenario	Average Annual Cost	
Fix-As-Fails	$8,746,700	
Advance Maintenance	$3,728,400	
Replace in 2000	$1,603,100	
Replace in 2001	$1,566,500	
Replace in 2002	$1,531,600	
Replace in 2003	$1,509,200	← OPTIMUM TIME TO REPLACE
Replace in 2004	**$1,491,800**	
Replace in 2005	$1,494,600	
Replace in 2010	$2,195,100	
Replace in 2020	$6,275,100	

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ORMSS Reliability Integration

Greenup Locks – Main Chamber Miter Gates

- **What Did Original Analysis Predict?**
  - ORMSS hazard rates and economic analysis indicated the optimal time to replace main chamber miter gates by 2004 without a major repair to these gates ahead of that time
  - Analysis was completed in 1999 based upon field performance of similar miter gates on Ohio River system and future traffic trends
- **What Actually Happened?**
  - Routine inspection dewatering of Greenup main chamber in fall 2003 planned for 21 days, no significant deterioration expected
  - Significant damage to gates found that emergency repairs required
  - Closure extended to 54 days (cost to industry and power companies estimated to be in $15 to $25 million range). Thus, gates suffered an “economic” failure.

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ORMSS Reliability Integration

Deterioration of Ohio River Miter Gates

Cracking Near Quoin Block

Cracking Through Thrust Plate

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Plan Development
Alternatives

- Maintenance Alternatives
  - Fix major components as they fail
  - Plan for major repairs and fix before they fail
- Operational Alternatives
  - Helper boats, schedule arrivals
  - Congestion fees
- New Construction Alternatives
  - Construct new 1200’ lock
  - Extend auxiliary lock so it is 1200’ long

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ORNIM Ohio River Navigation Investment Model

- Identify Optimal Investment Strategies Considering Probabilistic Analysis of Engineering, Economic, and Environmental Features
  - Multiple maintenance scenarios tied to reliability
  - Effectiveness of various repair scenarios
  - New construction versus sustaining existing system
  - Traffic management

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ORNIM

Analysis Capabilities of ORNIM

- System-wide benefits
- Handles engineering reliability
- Tradeoffs among projects over time
- Tradeoffs between new construction, repairs/maintenance, and traffic management
- Multi-year horizon

The ORNIM System

Random Closure Probabilities

Reliability Estimates

Repair Plans and Costs

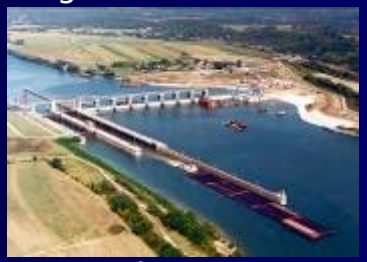
Construction Plans

Lock Risk Module

Cargo Forecasts

Optimal Investment Module

Waterway Supply and Demand Module



Towboat/Barge Operations

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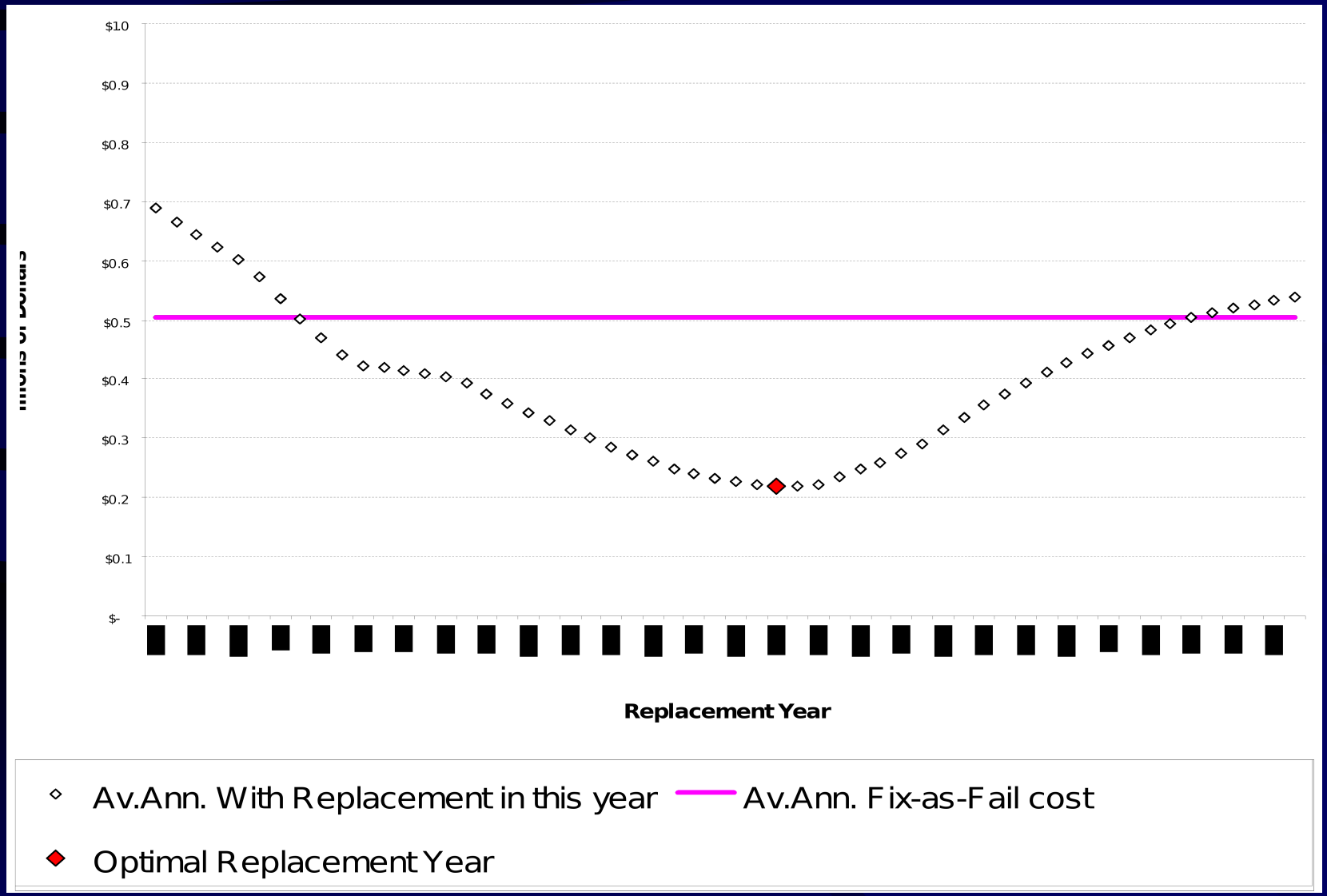
Budget

Optimal Investment in Projects and Maintenance

Lock Operations

River Network

ORNIM Reliability Output



ORNIM Economic Analysis

Optimal Component Replacement Dates

Chamber / Component	Forecast Scenario					
	Clear Skies	Clear Skies No Hg	NAAQS Flat	NAAQS Growth	Utility Based	Utility Based High
Main Chamber						
Miter Gates (Upper & Lower)	2035	2034	2034	2034	2035	2033
Miter Gate Machinery (Upper & Lower)	FAE	FAE	FAE	FAE	FAE	2058
Culvert Valves	FAE	FAE	FAE	FAE	FAE	2058
Culvert Valves Machinery	FAE	FAE	FAE	FAE	FAE	FAE
Hydraulic Systems	2015	2015	2015	2015	2026	2021
Electrical Systems	2015	2005	2005	2005	2026	2023
Auxiliary Chamber						
Miter Gates (Upper & Lower)	FAE	FAE	FAE	FAE	FAE	FAE
Miter Gate Machinery (Upper & Lower)	FAE	FAE	FAE	FAE	FAE	FAE
Culvert Valves	FAE	FAE	FAE	FAE	FAE	FAE
Culvert Valves Machinery	FAE	FAE	FAE	FAE	FAE	FAE
Hydraulic Systems	FAE	FAE	FAE	FAE	FAE	FAE
Electrical Systems	FAE	FAE	FAE	FAE	FAE	FAE

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Other Recent Applications

- Chickamauga Lock Replacement Study (Nashville)
  - Navigation lock on Tennessee River near Chattanooga
  - Mass concrete deterioration due to AAR
  - Reliability models for AAR-effected monoliths, including critical lower miter gate monolith
- Markland Major Rehabilitation (Louisville)
  - High traffic navigation lock on Ohio River
  - Fatigue and fracture of steel miter gates and culvert valves
  - Rehab approved at HQUSACE in FY00. Awaiting CG funds.

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Studies from ORMSS

- Great Lakes and St. Lawrence Seaway Study
  - Joint effort between USACE, USDOT, and Transport Canada
  - 18 locks, multiple ports, bridges, and tunnels
  - 4 year study evaluating long-term operation of system considering reliability, maintenance, future traffic trends
- Panama Canal Infrastructure Risk and Reliability Study
  - Phase I proposal being reviewed by ACP
  - Multiple year study looking at long-term reliability for various maintenance scenarios, risks associated with seismic events, flood analysis, and potential 3rd lane alternatives
  - Economic aspects include varying rates, traffic trends, etc…

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New Reliability Guidance Based Upon ORMSS

- Three Year Plan to Develop Infrastructure Reliability Guidance Engineering Circular (EC)

  1/3 of funds allotted for FY04, remainder split over FY05 and FY06

- Guidance will cover all major engineering disciplines (structural, geotechnical, mechanical, electrical, and hydraulics)

  Integration with economics and plan formulation also included

- HQUSACE Requested Team from ORMSS to Develop New Engineering Reliability Guidance to Cover All Infrastructure
- Intent is for New EC to Replace All Existing Guidance and Be Used for All Civil Works Infrastructure Rehab Evaluations

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THANK YOU

QUESTIONS ???

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